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OPTICAL FACTORS IN AIRCRAFT WINDSHIELD DESIGN AS RELATED TO PILOT VISUAL PERFORMANCE

Walter F. Grether

Aerospace Medical Research Laboratory
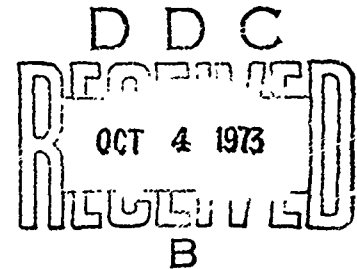Wright-Patterson Air Force Base, Ohio

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FOR THE COMMANDER

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13 ABSTRACT

The slope and curvature of aircraft windshields that are optimum for high speed flight cause optical degradation of pilot vision in the forward direction. This report presents a survey of the literature bearing on the conflict between aerodynamic and visual requirements. The optical effects of windshield slope (or angle of incidence) and curvature are reviewed, in terms of displacement, deviation, distortion, binocular deviation, reflections, multiple images, haze, transmission loss, and reduced resolution. Included in the review are discussions of windshield design practices in recent military aircraft, as well as optical standards and tolerance contained in current military specifications The review also provides a discussion and research data on pilot visual performance as affected by windshield design factors, and a small sample of pilot opinions concerning the visual problems caused by the windshield of the F-111 aircraft. The report concludes with some suggestions for further studies that would assist in making choices concerning windshield design.

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PREFACE

This report was prepared at the suggestion of Col Neville P. Clarke, Director of Research and Development, Headquarters Aerospace Medical Division, Brooks AFB, Texas. His suggestion resulted from increasing pilot complaints of visual problems caused by the windshield of the F-111 aircraft, from questions about pilot visual capabilities arising during the development of the windshield for the B-1 aircraft, and other indications of pilot visual problems related to windshield design. The work of preparing the report was carried out under Project 7184, Human Engineering for Air Force Systems.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION AND PURPOSE

Good vision for the pilot in the forward direction is a normal design requirement for all aircraft. It is a requirement, however, that has been increasingly difficult for the aircraft designer to achieve as flight speeds have increased. The basis for this conflict in design requirements is quite simple and well known. Optimum visibility calls for a flat windshield installed very nearly perpendicular to the pilot's line of sight. High speed flight, on the other hand, calls for a windshield that is thick, multilayered, coated for various purposes, curved, and slanted backward at a very shallow angle. All of these optical features produce unfavorable effects on vision.

The problem of providing good forward visibility becomes particularly critical in the design of supersonic aircraft. For supersonic transports the use of a hinged nose section permits good pilot visibility during takeoffs and landings. But during other regimes, when the nose is in the up position, forward vision is considerably degraded (Larry, 1966). About twenty years ago much thought was given by research and design personnel to the possible substitution of a periscope for the windshield in supersonic aircraft. Flight research by Roscoe and his associates (1951, 1966) demonstrated that pilots could take off, fly, and land an aircraft using only a periscope for forward vision. But, as a solution to the windshield problem for highspeed aircraft, the periscope never appeared to be acceptable. The visual problems inherent in the use of periscopes and other windshield substitutes in aircraft are discussed by Wulfeck et al. (1958). A recent paper by Beaumont (1973) describes some new periscope concepts that might make the periscope an acceptable alternative.

For military aircraft, even those designed for supersonic speeds, no use has been made of the hinged nose, periscope, or other similar innovation as a means of achieving good forward visibility. As a consequence, the windshields of high performance military aircraft, to varying degrees, have handicapped the pilot's forward vision. The difficulties experienced by pilots are discussed later in this report.

It might be argued that the needs for good forward visibility are no longer important because of modern reliance on ground control of air traffic, and the instruments, radar, and radio aids now available to flight crews. While it is true that the reliance on vision outside the aircraft has been reduced for some aspects of flight, forward vision is still of major importance. Aside from the pilot's natural desire to see ahead and be assured of clear passage, there are many pilot duties requiring good forward vision. The most critical of these for military aircraft are probably taxi, landing, in-flight refueling, collision avoidance, formation flying, and detection and sighting of tactical ground and air targets.

This report presents a literature survey of optical factors in aircraft windshield design and relates them to modern Air Force requirements for pilot's vision in the generally forward direction. The survey covers research and technical literature bearing on this subject. It also discusses current military specifications, requirements, design practices, and optical test methods. It is hoped that the information provided in this review will be helpful to persons responsible for windshield design in future military aircraft. This report is limited to the problems of pilot vision through the transparent portion of the forward windshield. There are many other important problems of vision from aircraft, such as overall fields of view and obstructions to vision, which are not covered or

only touched on lightly. For information about these and other problems of pilot vision the reader is referred to the report, *Vision in Military Aviation*, by Wulfeck et al. (1958).

Very helpful to the author in preparing this review were a number of general review articles and reports bearing on the problems of visibility through aircraft windshields (Cocagne and Blome, 1968; Corney, 1973; Corney and Shaw, 1971; Glover, 1955; Grether and Muick, 1964; Holloway, 1970; Pinson and Chapanis, 1946; and Provines and Kislin, 1971).

2. WINDSHIELD GEOMETRY

Two aspects of windshield geometry are of particular importance in terms of their effects on pilot vision. These are angle of incidence and radius of curvature. Angle of incidence is measured with respect to the pilot's horizontal sighting line and a line normal to the windshield surface (see Fig. 1A). A high angle of incidence is generally desirable for aerodynamic reasons to achieve minimum disturbance of the airflow along the fuselage.

Windshields may be either flat or curved panels or a combination of these. Amount of curvature is defined in terms of the radius of the curvature. If the curvature is about one axis and the surface represents a section of a cylinder, it is referred to as single curvature. The surface may also represent a section of a sphere or other complex shape so as to conform with the adjacent aerodynamic shape, and is referred to as having double or compound curvature. Curved windshield panels in military aircraft quite often represent a section of a cone, thus having a range of curvatures about a single axis.

The use of curvatures is aerodynamically beneficial. It also makes possible what might be called a wrap-around effect, giving a larger forward view without visual obstruction by supporting members. In fighter aircraft, a fairly standard windshield has consisted of a flat, sloping front panel, with two curved side panels. With this design, of necessity, there are obstructions to vision by the framing that joins the front and side panels. However, if the frame members are narrower than the distance between the two eyes (about 2.25 in.) there are no areas in which vision is completely cut off. By using curved windshields in single place or tandem aircraft, one wrap-around panel can replace the combination of a flat front and two curved side panels. Such a one-piece windshield has the advantage of providing a larger clear field of view, but introduces some very undesirable optical effects.

3. DEFINITION OF OPTICAL TERMS AND THEIR EFFECTS ON VISION

To provide a basis for the material which follows, this section describes the optical effects that will be discussed, and shows how they interrelate with each other. Many of these effects are illustrated in Fig 1. For purposes of illustration the effects are considerably exaggerated. Also the effects are illustrated for simple single-layer windows, rather than laminated transparencies as
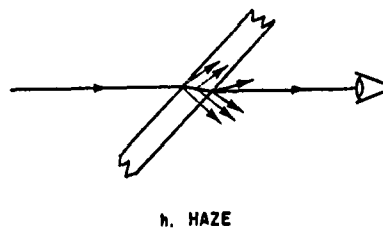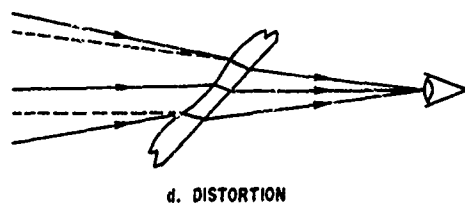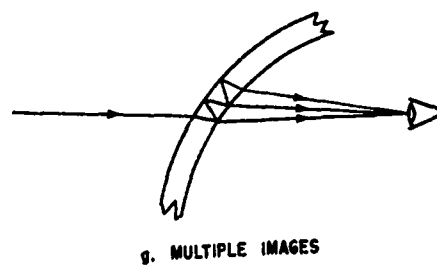
a. ANGLE OF INCIDENCE

e. CURVATURE (CAUSING DEVIATION)

b. DISPLACEMENT

f. INTERNAL REFLECTIONS

c. DEVIATION

g. MULTIPLE IMAGES

d. DISTORTION

h. HAZE
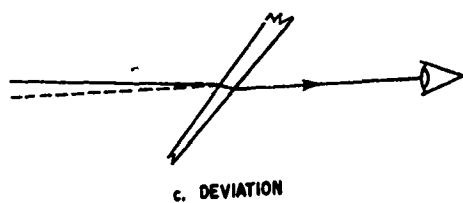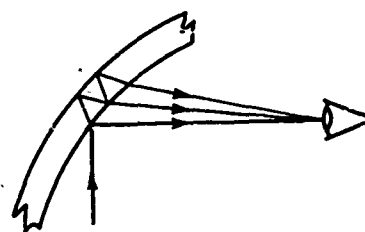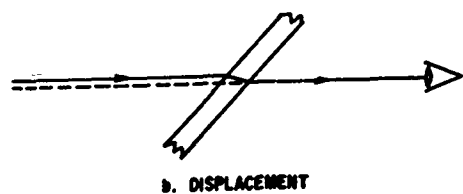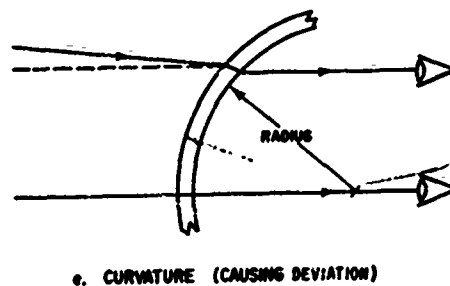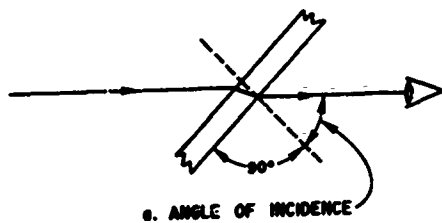
Figure 1. Optical effects related to aircraft windshield design.

normally used in windshields. Each layer of a laminated transparency can contain any or all of the optical effects shown.

A. ANGLE OF INCIDENCE

(See preceding section and Fig. 1A.)

B. DISPLACEMENT

In passing through a window with parallel surfaces, light rays are bent and displaced as shown in Fig. 1B. The displacement is zero for 0° angle of incidence, and increases as the angle of incidence, thickness, or index of refraction are increased. The displacement is linear and usually measured in millimeters or fractional inches. It does not increase with distance and the effect on pilot vision probably is not significant.

C. DEVIATION

In passing through a window with nonparallel (wedge) surfaces the path of light is deviated angularly as shown in Fig. 1C. The amount of deviation is expressed in terms of the angular change (degrees, minutes, or seconds.) Deviation increases with index of refraction of the window material, the amount by which the surfaces deviate from parallelism, and the angle of incidence. Deviation causes objects to be seen at other than their true direction from the observer (pilot).

D. DISTORTION

If a window has minor variations in thickness, or in parallelism of the two surfaces, there will be variations in deviation for different parts of the window (see Fig. 1D). This effect will cause straight lines to appear wavy, and the shapes of objects to appear distorted. As moving objects are seen through different parts of the window their motion and shape will change irregularly. Distortion increases with index of refraction and angle of incidence. Also, curved windows normally cause much more distortion than flat windows. The measurement and quantification of distortion are discussed later.

E. CURVATURE

Light rays passing through curved glass at zero angle of incidence to the radius of curvature will enter and exit with no deviation of the light path (see Section 2 and Fig. 1E). For all other angles of incidence relative to the radius of curvature the light will exit with some deviation, even though the surfaces are perfectly concentric. The deviation increases with increasing angle of incidence, index of refraction, thickness of the transparency, and with decreasing radius of curvature.

F. INTERNAL REFLECTIONS

Lights or bright objects inside the crew station can be reflected into the pilot's eyes from the inside surface of a window (see Fig. 1F). Under many circumstances, ground lights, such as lights from a city, will also reflect from the inside windshield surface into the pilot's eyes. Such internally reflected images will appear superimposed over the area seen through the windshield, and therefore will obscure vision for objects outside. These internally reflected images are normally troublesome only under night conditions. Under particular conditions these reflections may be multiple, as in the case of multiple images discussed below.

4

G. MULTIPLE IMAGES

On passing through a window, some light is reflected at each surface as the light enters and leaves. The proportion reflected is minimal at zero angle of incidence, and increases to 100% as the angle approaches 90°. Under some optical conditions the reflections inside the transparency may result in one or more secondary images, as illustrated in Fig. 1G. For a laminated panel there may be additional images caused by reflections at the laminations. Since these secondary or ghost images are less bright than the primary image, they are normally seen and become a problem only at night. The optical conditions most likely to produce multiple images are curved panels, or flat panels with wedginess, combined with high angles of incidence. A metallic coating on the transparency increases the intensity of the secondary images. Such multiple images will occur with flat panels only if there is sufficient wedginess to reflect the displaced image or images back to the observer's eyes, rather than along a path parallel to the exit path of the primary image. Multiple images can normally be avoided by use of high quality flat panels.

H. BINOCULAR DEVIATION

If there is curvature in the horizontal plane, the deviation due to curvature will be different for the two eyes (as shown in exaggerated form in Fig. 1E), since the two eyes see through different parts of the curved window. This causes an effect called binocular deviation (Corney and Shaw, 1971; and Corney, 1973). It is believed that the eyes can readily adjust to small amounts of binocular deviation. However, when the collimated image of a gunsight or heads-up display is superimposed over the view through a curved windshield the binocular images may not be compatible (see section 6, also Fisher, 1973). Curved windows are more difficult to manufacture than flat windows, and therefore more likely to have defects causing deviation and distortion, which also will cause binocular deviation effects. These will vary for different parts of the windshield.

I. HAZE

As light enters or passes through a window some of the light may be scattered and appear as haze or fog in the window (see Fig. 1I). Such haze is increased by dirt, scratches, or abrasions on the window surface. Haze is generally defined in terms of the percent of light scattered and therefore lost in passage through the window. The haze effect is increased as the angle of incidence is increased. It is minimized if windshields are clean and free of abrasions. Haze contributes greatly to glare when looking toward the sun or other high intensity light sources. It also reduces the contrast of objects seen through the windshield.

J. TRANSMISSION

Some light is lost by absorption within the transparent material. This normally is a rather small percentage of the light, except for very thick windows. In aircraft windshields the use of electrically conductive and radar reflective coatings contribute to light loss by absorption. Most of the transmission loss is due to reflections, and this loss increases with angle of incidence. Most important, however, is the total light transmitted, regardless of whether the loss is due to surface reflections, haze or absorption. Transmission is measured in terms of the percent of incident light that reaches the observer. During daytime reduced transmission is quite tolerable and even desirable. At night, when vision is already marginal, reduced light transmission will further reduce the visual capacities of the pilot or other observer.

K. RESOLUTION

Resolution refers to visual acuity, or the ability of the observer to resolve fine detail. Under

typical daytime conditions, using a rough rule of thumb, a person with normal vision can resolve lines separated by one minute of arc. A windshield may cause some loss of resolving power, particularly if dirty, scratched, or of poor quality material. Some of the factors discussed earlier, namely haze and reduced transmission, are the major factors affecting visual acuity of the observer in looking through a window.

4. WINDSHIELD DESIGN PRACTICES WITH REGARD TO ANGLE OF INCIDENCE AND CURVATURE

In terms of its effect on pilot vision, angle of incidence is one of the two most important optical parameters in windshield design. The other critical design factor is use of curved versus flat panels. Based upon studies conducted during World War II (Pinson and Chapanis, 1946), the windshield design standards for many years set the maximum angle of incidence at 60°, and required the use of flat panels. As aircraft speeds have increased, the Air Force has permitted higher angles of incidence and the use of curved windshield panels.

The current Air Force Systems Command Design Handbook (AFSC-DH-2-1, DN 3A1, 1 October 1969) requires "that the angle of incidence throughout the windshield panel does not exceed 60°." Similarly, the US Navy (Mil-W-81752(AS), 23 April 1970) states that "in no case shall the angle of incidence exceed 60° for a line of vision from the pilot's eyes to any point in the transparent area used during approach and landing as required by MIL-STD-850." Both of these design specifications, as written, set the maximum angle at 60°, not only for the horizontal line of sight, but for all parts of the forward windshield.

Angle of incidence requirements are also provided in MIL-STD-850B, dated 3 November 1970, as follows, "at the intersection of the horizontal vision line and the windshield, the angle of incidence shall not exceed 60°." This specification does not prohibit a larger angle of incidence in other than the forward central portion of the windshield. Also provided in MIL-STD-850B are requirements for visual clear areas to be provided. For the pilot position in single and tandem fighter/attack aircraft, at zero degrees azimuth, there is a requirement for 11° downward and 10° upward vision. For side-by-side fighter/attack aircraft these requirements are 13° downward and 12° upward. For bomber/transport aircraft they are 17° downward and 20° upward. Using these requirements for downward vision, and the angle of incidence requirements of MIL-W-81752, the horizontal angle of incidence requirements are 49° for tandem and single-place fighter/attack, 47° for side-by-side fighter/attack, and 43° for bomber/transport aircraft.

Table 1 provides data on angle of incidence and curvature of windshields in some of the recent Air Force and Navy aircraft. It is apparent from this table that the Navy continues to prefer flat windshield panels, and retains angles of incidence to the horizontal sight line of 60° or less. By comparison, the Air Force, for some of the newer aircraft, has chosen curved windshields, with angles of incidence considerably exceeding the 60° standard. It would appear from this difference in design practices that the Navy places a higher premium on pilot vision requirements because of the need for visually guided landings on aircraft carriers. This would seem to be the major difference between the Navy and Air Force in demands on pilot vision.

TABLE 1. WINDSHIELD GEOMETRY OF SOME RECENT MILITARY AIRCRAFT*

Aircraft Type No.	General Windshield Configuration	Horizontal Angle of Incidence	Downward Vision Angle at 0 Azimuth	Radius of Curvature
F-4	Flat front plus two curved side panels	62°	15°	Flat
F-14	Flat front plus two curved side panels	60°	15° 38′	Flat
A-7	Flat front plus two curved side panels	60°	15° 45′	Flat
AX (A-10)	Flat front plus two curved side panels	45°	20°	Flat
F-106	V-type, two panels	70°+	15°–17°	Flat
F-111	V-type, two panels	68.4°	11.5°	18–31 in.
B-1	V-type, two panels	65°	15°	50 in.
T-38	One-panel	62.5°	11.5°	13.2–16.4 in.
F-5	One-panel	66°	11°	14.3–16.0 in.
F-15	One-panel	62°	15°	16–18 in.

*These data were provided by Robert E. Wittman, of the Improved Windshield Development,
Advanced Development Program Office, USAF Flight Dynamics Laboratory, Wright-Patterson AFB.

5. OPTICAL EFFECTS OF ANGLE OF INCIDENCE

As the angle of incidence is increased, a number of optical effects occur that are unfavorable to vision. Some of these effects are caused by the increased thickness of the transparent material through which the light must pass. Other effects are due to a greater proportion of the light being reflected at the surfaces, including surfaces of laminations. The most serious effects, however, result from magnification of deviation and distortion caused by wedginess and irregularities in the surfaces of the window.

Shown in Fig. 2 are the changes in deviation and distortion with angle of incidence. The data on deviation are from AFSC Design Handbook 2-1, and the data on distortion from Cocagne and Blome (1968). The curves show the multiplication factors by which the value at zero angle of incidence is increased. If, for example, a piece of glass caused a deviation of 10 minutes of arc at zero angle of incidence, this value would be increased to approximately 50 minutes of arc at 70°. For distortion the curve is read in the same manner, except that the measurement is in terms of maximum line slope change on a rectangular grid photographed through the test window.

Similar data on effects of angle of incidence are shown in Fig. 3 for surface reflections, and for transmission through a window (from AFSC Design Handbook 2-1). The reflection data apply to the surface where light enters a window. For reflections inside the window, at the surface where light exits, the same data apply, but only to the angle of light rays before entering the window. For light rays inside the window the curve is shifted to the left by an amount depending on the index of refraction of the material. The transmission losses shown in Fig. 3 are due, in large part, to the light lost by reflection.
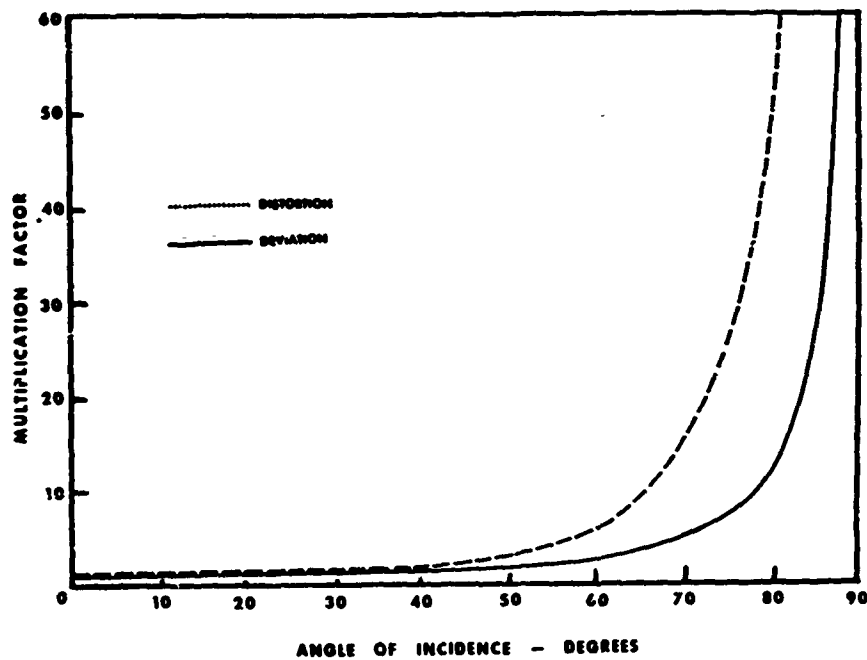
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Figure 2. Effects of angle of incidence on optical deviation (from AFSC Design Handbook 2–1, 1969) and distortion (from Cocagne and Blome, 1968).
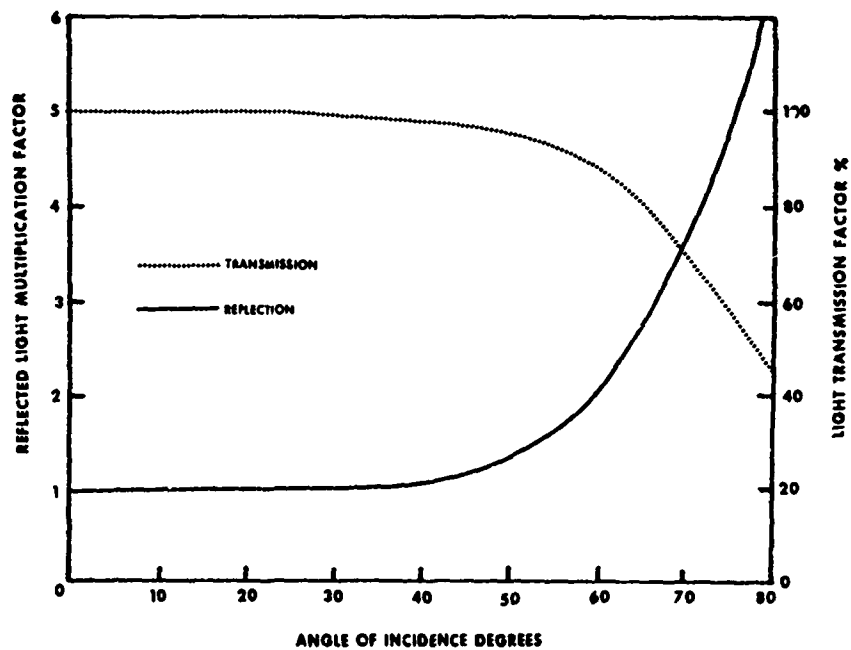

Figure 3. Effects of angle of incidence on surface reflections and transmission loss (from AFSC Design Handbook 2–1, 1969).

8

All four curves shown in Fig. 2 and 3 have basically the same form, and show that deviation, distortion, reflections, and transmission loss all increase rapidly as the angle of incidence exceeds 60°. For all curves, the change between 60° and 70° is greater than that between 0° and 60°. It is primarily from these data that the design standards referred to earlier were derived, which set 60° as the maximum allowable angle of incidence for military aircraft windshields.

6. OPTICAL EFFECTS OF CURVATURE

As shown in Fig. 1E, a light ray passing through a curved window at other than zero angle of incidence with reference to the radius of curvature, will be given some angular deviation, even though there are no defects and the window surfaces are perfectly concentric. In addition to the angle of incidence, the amount of this deviation depends upon the radius of curvature, the thickness of the window, and the index of refraction. If a pilot's eye position is at the radius of curvature of a curved windshield, he will experience no deviation caused by the curvature itself. Most likely there will be deviation from wedginess in the transparency, since it is much more difficult to avoid such defects in curved as opposed to flat windows.

The extent to which deviation is affected by radius of curvature and angle of incidence is illustrated by data from Pinson and Chapanis (1946) shown in Fig. 4. In these curves thickness and index of refraction are held constant. More commonly such data are plotted in terms of the ratio of thickness to radius of curvature (thickness ratio) rather than radius alone. Such a plot is shown in Fig. 5, using data from Holloway (1970). As can be seen from these curves, a combination of a thick window (as used in aircraft windshields), high angle of incidence, and short radius of curvature can result in very high angles of deviation. It is very important, therefore, where curved windshields are used, to keep the radius of curvature as large as possible, and to position the windshield so that the pilot's eyes will be near the center of the curvature. In addition, the curvature should be single rather than compound.

Another undesirable optical effect caused by curvature is the production of multiple images, as shown in Fig. 1G. With flat panels, having parallel surfaces, the internally reflected rays exit in parallel with the primary ray, and thus are not seen. With a curved or distorting window, however, the internally reflected rays exit at a different angle from the primary ray, and may converge with it at the observer's eye. This causes the observer to see the same object or light source at two or more locations. Such multiple images are most likely to occur at large angles of incidence and high thickness-curvature ratios. Also, the images are increased in brightness and separation as the angle of incidence is increased.

Reflections from the inner surface of a windshield, from lights or lighted objects in the cockpit, are much more troublesome with curved panels. With flat sloping windshields, combined with a glare shield, most such reflections can be prevented from reaching the pilot's eyes. Curved panels provide many more possible reflection angles, thus increasing the potential light sources that may be seen reflected from the windshield.

The most critical sighting area in a fighter-type aircraft is the central portion of the windshield, which is used in conjunction with the reflector-type of gunsight. For aircraft using such a sight a

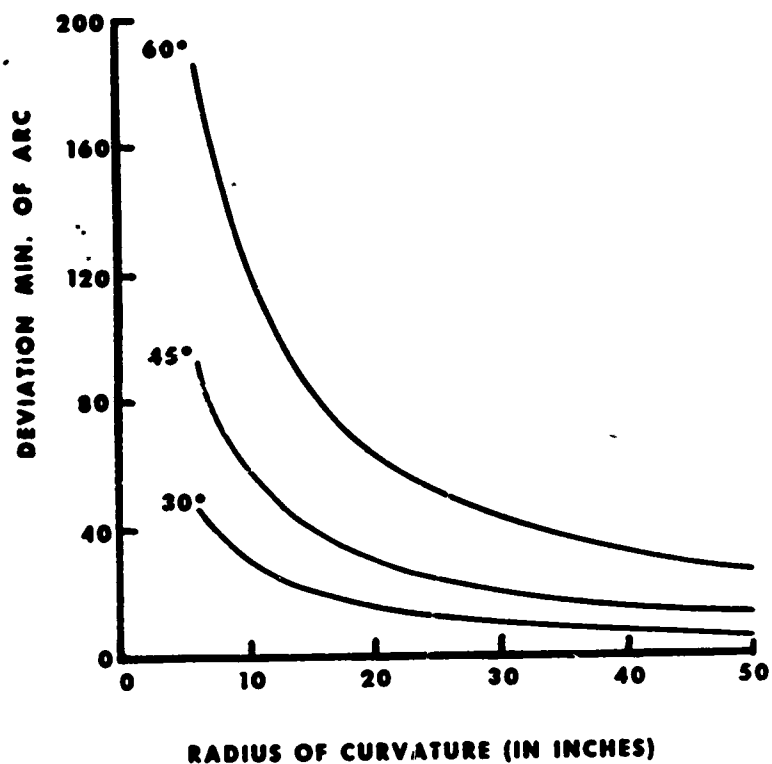**Figure 4. Effects of radius of curvature on optical deviation at three angles of incidence (from Pinson and Chapanis, 1946).**
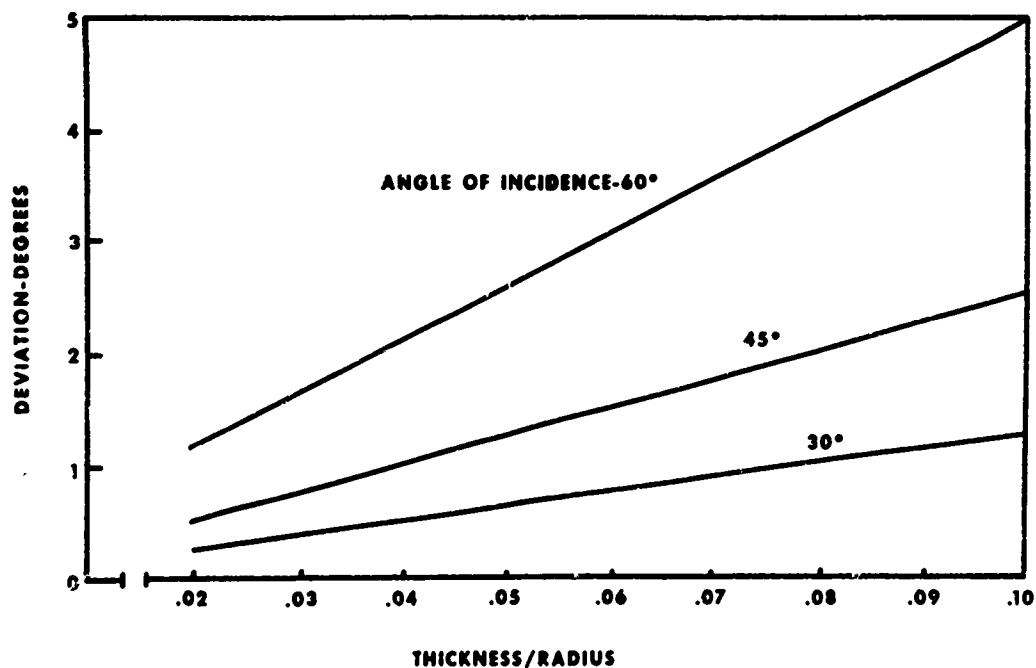

Figure 5. Effects of thickness/curvature ratio on optical deviation at three angles of incidence (from Holloway, 1970).

higher quality of transparency is required, identified as Type II. For the critical gunsight area the applicable document (Mil-G-5485C, 23 April 1971), specifies the maximum allowable optical deviation as "31.5 seconds of arc (60 seconds wedge angle)." This deviation is measured at 0 angle of incidence, not the installed angle. The specification also calls for flat glass with a minimum radius of curvature of 500 ft. Some newer aircraft, however, use a curved windshield in combination with reflector-type gunsights.

When a reflector-type gunsight or other heads-up display is used in combination with a curved windshield, there are problems in compatibility of the images being superimposed. This occurs because the angle of incidence for seeing through a curved windshield is slightly different for the two eyes, causing the condition called binocular deviation. The image from the heads-up display is collimated and reflected off a flat window, and has zero binocular deviation. Hence the eyes cannot fuse the two pictures and double images are the result. This problem has been described and studied by Fisher (1973), who has worked out what appears to be an acceptable solution using optical compensation in the heads-up display.

7. VISUAL PERFORMANCE OF PILOTS AS AFFECTED BY WINDSHIELD DESIGN

Since the beginnings of aviation, high importance has been assigned to pilot visual capability. Pilots are required to meet high standards of visual acuity, color vision, muscle balance, and absence of visual defects in both eyes. The basis for such requirements is the high premium that the pilot's duties place on visual information imputs from both inside and outside the aircraft. Because of a general trend in aviation toward increased reliance on radar, radio, and instrument aids, the needs for outside vision have been reduced for some piloting tasks, such as collision avoidance. On the other hand, the higher cruise and landing speeds have increased the distances at which visual information must be picked up in time to respond to it.

Requirements for external vision are least critical in passenger, cargo, and large bomber aircraft under noncombat conditions. Even in these, however, the pilot is still dependent on good external vision for performing many tasks. During taxi he must be able to see hand signals of ground personnel, and lights, markings, obstructions, and pavement conditions, along the taxi way. During take-off he must be able to see and interpret runway lights, runway signs, runway markings and obstructions or other hazardous conditions. During approach and landing the pilot also must be able to see lights, signs, runway markings and obstructions. But the most critical visual task probably is judging height above the runway during flare-out before touchdown. Enroute the visual requirements for collision avoidance have been somewhat reduced by present day ground control of air traffic. But, in clear weather the pilot is still required to see and avoid other aircraft.

There are additional demands on pilot vision in combat type aircraft, depending on the aircraft type and military mission. During aerial refueling vision is critical for the pilot of the receiver aircraft to hold the proper position below and behind the tanker. This task requires good vision in the forward and upward direction. Formation flying, in a similar way, requires good vision to either side in the forward direction. Flight at low altitude requires good vision forward and downward over the nose. Fighter aircraft require good vision for sighting and attacking aerial targets.

Fighter/attack aircraft, in addition, require good vision for sighting and attacking ground targets. Most fighter aircraft have reflector-type gunsights, which place special demands on windshield optics, as discussed earlier.

Under wartime combat conditions the visual capability of pilots becomes even more critical, particularly in fighter and fighter/attack aircraft. In spite of modern radar and other substitutes for direct vision, much of the actual detection and attack of aerial and ground targets during daytime is carried out by direct vision. Combat effectiveness and survival depend very much on visual detection range, visual target identification, and visual sighting accuracy with reflector-type gunsights.

What are the particular visual functions that are required in order for the pilot to perform the types of tasks described above? How much degradation of these visual functions by windshield optics can be considered acceptable? Or more to the point, what are the appropriate tradeoffs between pilot vision through the windshield and aerodynamic penalties to the airframe shape? These are difficult questions, and the answers must currently be based largely upon analysis and judgement rather than research data. An attempt was made to find research data that might help answer these important questions, but this search was largely futile.

The visual function most important for performing critical pilot tasks is visual acuity in a general sense. This includes ability to detect small targets (minimum perceptible acuity), ability to resolve detail (minimum separable acuity), ability to judge small displacement of lines (vernier acuity) and ability to see detail in moving targets (dynamic acuity) (see Grether and Baker, 1972).

The other important visual function is depth perception, also in a broad sense. Depth perception based upon binocular disparity of the images in the two eyes is important only during ground operations, formation flying, and aerial refueling. Otherwise, most of the depth or distance judgements are made at distances of 1,000 ft or more, where binocular disparity is ineffective. More important distance or depth cues are object size, texture, linear perspective (such as convergence of parallel lines) and relative motion. All of these, of course, depend to some extent on visual acuity. Very detrimental to depth perception are optical deviation and distortion, because of their effects on linear perspective.

Of obvious importance in the performance of pilot tasks is the appearance of visual targets in their true direction and their true form as seen from the pilot's eye position. In landing, for example, the shape and size of the visual image formed by the runway are vital clues to the pilot as to his position relative to the proper slope and distance from the point of touchdown. From the pilot's position on the glide slope the runway appears as a trapezoid of a particular shape. Displacements above or below the proper glide slope will cause the trapezoidal image to be elongated or flattened vertically. Displacements to the right or left will cause the shape to be distorted horizontally. Also, the pilot judges where his glide path will terminate by the point on the ground (hopefully near the runway threshold) which is stationary in his windshield. Other ground objects move radially from this point relative to the windshield. For the pilot to use these cues effectively requires good visual acuity, minimum deviation and distortion, and minimum interference from windshield haze and reflected false images. But what are the minimum levels of these that are tolerable and acceptable? Human factors research data that can be used to set tolerance levels for windshield optical degradation of visual functions are indeed scarce. Apparently the need for maximum visual capability has been taken for granted and research has not been considered necessary.

Pilot vision is often degraded by common environmental conditions, such as darkness, haze, fog, clouds, rain, snow, and glare. Vast amounts of aviation research and development have been required to overcome these obstacles to aviation, and to make it possible to fly under almost all weather conditions. Even so, it is generally accepted that the hazards of flight are increased, and combat effectiveness is decreased, when environmental conditions reduce the range and clarity of pilot vision. Handicaps to vision are common contributory factors in aircraft accidents, although the primary cause is usually classified as pilot error.

A report by Rayman (1972) shows that pilots who have been given waivers for failure to meet visual standards can cause accidents. His study lists 153 accidents in which pilots and navigators, with waivers for visual deficiencies, were involved. Of these waivers, 143 were for hyperopia or myopia, which are correctable by wearing glasses. In nine of the hyperopia and six of the myopia cases it was judged that the waivered condition contributed to the accident. In most of these accidents the pilots were not wearing their glasses, and therefore were flying with reduced visual acuity.

The effect of windshield transmission loss on visual acuity can be estimated from human visual acuity data, such as shown in Fig. 6 (from Blackwell, 1946). Also shown in Fig. 6 is the reduction in visual sighting range which results from the reduced acuity at the lower luminance levels. This curve shows that at daytime background luminance levels, 10 milli-Lamberts and above, the luminance level has very little effect on visual acuity and visual sighting range. As luminance is reduced to nighttime levels, however, visual acuity falls off quite rapidly. Thus light transmission loss has little effect on acuity during daytime, but is quite harmful at night. The ratio of transmission loss to acuity loss is about 10 to 3 at night. That is, if a windshield transmits only 10% of the incident light, this will cause the threshold visual angle to be increased by a factor of about 3.
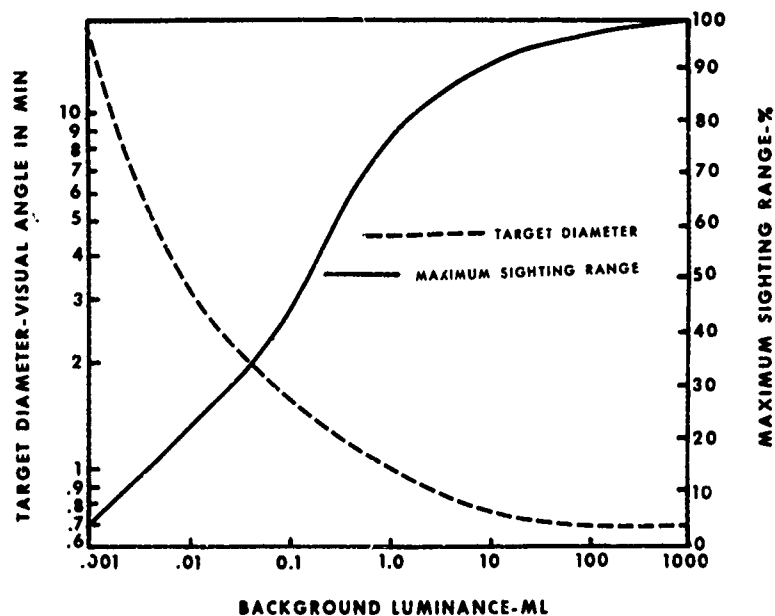

Figure 6. Effect of luminance level on minimum perceptible visual acuity and maximum sighting range (from Blackwell, 1946).

13

A windshield transmission factor as low as 10% is rather extreme, and probably greater than would be found in any existing military aircraft. Rather high transmission loss is anticipated, however, in the windshield of the B-1 aircraft, as shown by data from Mahaffey (1973). Windshield transmission will be approximately 40% for the horizontal sighting line, and 20% for downward vision over the nose. During development of the US Supersonic Transport by the Boeing Company, very low windshield transmission values were expected. A study by Larry (1966) predicted transmission values as low as 8.8% for the lower and 15% in the upper sections of the windshield in the nose up condition. Larry also reported a related flight test program in which these and higher transmission factors were evaluated in B-727 aircraft. Using a Cooper-Harper (1968) type scale the pilots rated the adequacy of vision for a variety of flight conditions. An overall summary of the pilot's ratings is shown in Table 2. Ratings of 4 and higher on the 9-point scale were considered unsatisfactory (U in Table 2). The data in the table include daytime, dusk, and night conditions, and takeoff, cruise and landing phases of flight. Ratings of unsatisfactory occurred much more frequently for the dusk and night than for the daytime conditions. Most of the unsatisfactory ratings were at the level of 4, although there were a few as high as 6 and 7.

TABLE 2. FLIGHT CREW RATINGS OF THE EFFECTS OF LIGHT LOSS CAUSED BY REDUCED WINDSHIELD TRANSMISSION (Larry, 1966).

Rating Basis	Transmission Range			
	8.8–15%		12–21.7%	
	Ratings		Ratings	
	S	U	S	U
Total visual adequacy and safety	51	11	32	5
Estimation of visual range	43	13	34	5
Estimation of apparent contrast	40	12	30	8
Detectability of objects important to safe flight operations	51	.	45	19

It appears from the pilot ratings obtained in Larry's study that windshield transmission factors in the range from 10 to 20% caused a considerable reduction in visual capability. This reduction showed up considerably more in the dusk and nighttime ratings, as would be predicted from the relation between visual acuity and luminance shown in Fig. 6.

A somewhat similar flight test was carried out in the Air Force by Mohr et al. (1973), in an evaluation of pilot acceptability of a proposed atomic flash protection method. This study was carried out in a T-38 aircraft. Windshield transmission was reduced to approximately 10%. In addition the visual area was reduced to a window 6 inches high and 8 inches wide placed about 10 inches from the pilot's eyes. Cooper-Harper-type ratings on a 9-point scale were obtained from 7 pilots. Each pilot made two night flights. On the first flight his vision was restricted only by the window. On the second flight a filter was placed in the window which, added to the T-38 windshield loss, reduced the total light transmission to about 10%. Ratings were obtained for different visual tasks required during taxi, takeoff, and landing.

The pilot ratings from the study by Mohr et al. are summarized in Table 3, in terms of overall average and maximum ratings on a 9-point scale. As the scale was set up, normal vision in the T-38 aircraft was assigned a rating value of one. This study did not obtain ratings of reduced windshield transmission independent of the area restriction. It appears that the reduced transmission had somewhat less effect on the pilot's ratings than did the restriction in visual area. From the verbal comments of the pilots, however, it was clear that some visual capabilities were significantly impaired by the reduced light transmission. For example, anti-collision lights of other aircraft were first detected at considerably shortened distances. Also, the distance was reduced at which the colors of VASI approach lights could be correctly interpreted. One pilot almost failed to notice the lights of another aircraft ahead of him while taxiing.

TABLE 3. PILOT RATINGS ON 9-POINT SCALE OF ABILITY OF TAXI, TAKEOFF AND LAND WITH RESTRICTIONS IN WINDSHIELD AREA AND LIGHT TRANSMISSION (Mohr et al., 1973).

Flight Phase	Visual restriction by window only		Visual restriction by window plus 10% transmission	
	Average ratings	Maximum ratings	Average ratings	Maximum ratings
Taxi	2.2	5	2.5	5
Takeoff	2.3	5	2.5	5
Approach & landing	2.5	5	2.8	6

Acceptability of tinted windshields in both aircraft and automobiles has been studied in relation to transmission loss. Allen (1970) has reviewed the data for and against tinted windshields in automobiles, and concluded that tinting is undesirable for driving at night because of the reduction in visual acuity. Allen quotes 70% as the minimum light transmission value recommended by the Society of Automotive Engineers for automobile windshields. Crosley (1968) has studied the desirability of tinted windshields for use in Army aircraft. He has likewise recommended that tinted windshields not be used, because of the reduction in visual efficiency at night. Clark (1971) in Australia analyzed an aircraft accident in which he believes that the light transmission of the tinted windshield was approximately 61%. During a night flight the pilot failed to see a mountain peak in time to avoid it.

A study by Schacter and Chapanis (1945) showed the effect of some windshield factors on depth perception, as measured by the Howard-Dolman test. Their data are summarized in Fig. 7, which shows how the depth perception threshold was degraded as the angle of incidence was increased. Also shown is the effect of the quality of the window material. Another study by Loper and Stout (1969) also used the Howard-Dolman test, and measured the effects of window distortion on test scores. Their data are shown in Fig. 8. The Howard-Dolman test measures primarily one aspect of depth perception, namely, binocular disparity. Since this depth cue is only effective at rather short range, it probably has minimal importance in aviation. Most likely depth cues, such as relative size, linear perspective, and relative motion would also be degraded by distortion, but no relevant research data were uncovered in this review.

An important pilot visual capability is the visual range at which targets, such as other aircraft,

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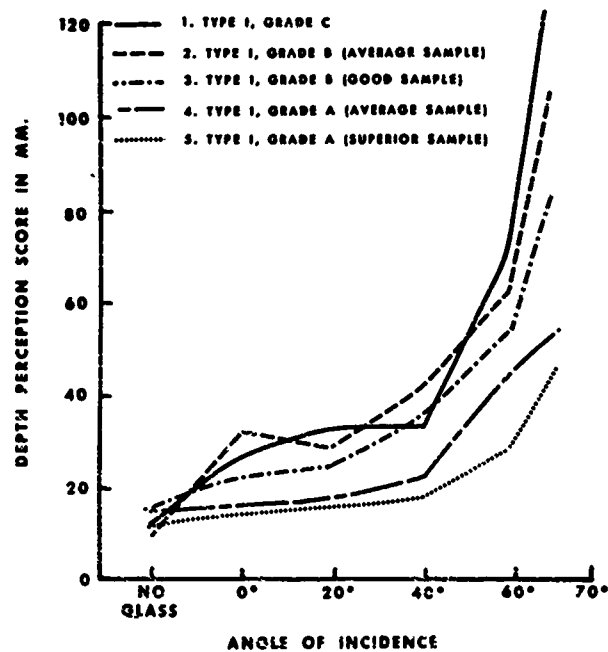
Figure 7. Effect of angle of incidence and windshield quality on binocular depth perception (from Schachter and Chapanis, 1945).
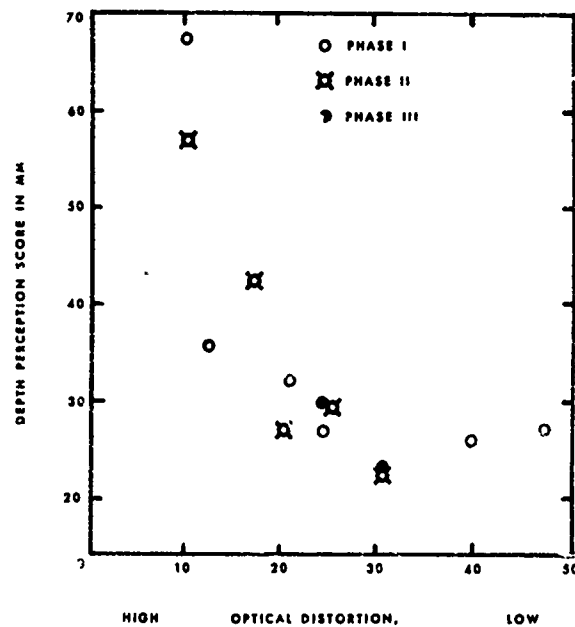
Figure 8. Effect of optical distortion on binocular depth perception (from Loper and Stout, 1969).

16

can be detected. Any factors that degrade visual acuity, primarily haze and transmission loss, will reduce the range at which targets can be detected and identified. A study by Luczak (1943) showed how the quality of the transparent material and the angle of incidence affect visual detection range. His major results are presented in Fig. 9. His results, like those of Schacter and Chapanis (1945) emphasize the importance of quality and surface condition of the transparent material.
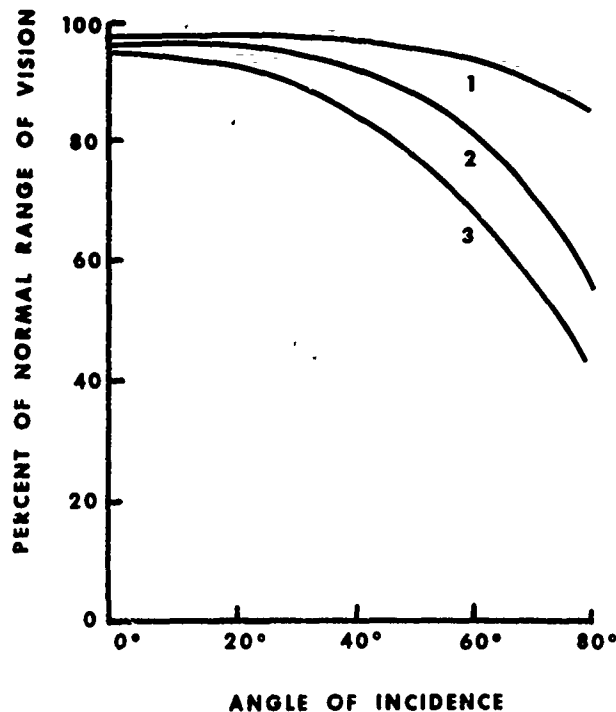
Figure 9. Effect of angle on incidence and windshield quality on visual target detection range: (1) plate glass; (2) clean plastic; (3) dirty plastic (from Lucazk, 1943).

8. PILOT ATTITUDES CONCERNING WINDSHIELD OF F-111 AIRCRAFT

In this survey no attempt was made to gather representative pilot attitudes concerning adequacy of windshields in different aircraft types. However, the F-111 windshield represents an extreme departure from the former use of flat panels and 60° maximum angle of incidence. For this reason a small sampling was made of observations of F-111 pilots concerning visibility in that aircraft.

The F-111 aircraft has side by side seating, with the pilot on the left and the observer on the right. The forward windshield consists of two curved panels on either side of a common structural support at the midline. This windshield divider slopes up to a canopy bow somewhat forward of the eye positions of the two crew members. For vision directly ahead the angle of incidence is about

69°, and the radius of curvature ranges from 18 in. at the front to 31 in. at the rear part of each panel. The eye position of the pilot is considerably to the left and above the center of curvature.

Seven F-111 pilots were interviewed during a visit to the Tactical Fighter Weapons Center, USAF Tactical Air Command, Nellis AFB, Nevada. Arrangements for the visit were made through Maj. W. P. Leggett (TFWC/TEM), who was the primary point of contact at the Tactical Fighter Weapons Center. Although the sample of pilots was small and not necessarily representative of all F-111 pilots, their observations do indicate a number of rather serious deficiencies that appear to be inherent in the windshield design. A personal inspection of the crew station of an F-111 in a hangar helped in providing an understanding of the pilots' complaints. The major deficiencies described by the pilots were the following:

A. BLIND AREAS FROM OBSTRUCTIONS TO VISION.

The structure dividing the two windshield panels, and the overhead canopy bow just forward of the two crew members, are considerably wider than the distance between the two eyes. Thus blind areas are created which cannot be overcome with binocular vision (see Wulfeck et al. 1958). These blind areas occur at both sides of each crew member, as well as overhead and forward. The pilots found these obstructions to be at such locations that they handicapped vision needed for formation flying and aerial refueling operations. There were also visual obstructions that were quite unrelated to windshield design. In particular, the pilots complained quite strongly about the visibility obstructions caused by side by side, as opposed to tandem, seating. Also they found the vision over the side and to the rear much more restricted in the F-111 than in older fighter aircraft.

B. OPTICAL DISTORTION.

All of the pilots seemed to have experienced some optical distortion. It was reported that some windshield panels with particularly bad distortion had been replaced, thereby somewhat alleviating the problem. Distortion was reported to be greatest at the edges of the windshield and minimal for central forward vision. Some pilots reported uncertainty about the height above the runway during landing, because of windshield distortion. They indicated, however, that this was not a serious handicap in the F-111, since landings were typically conducted without flare-out before touchdown. At least one pilot reported that during low altitude flight, he depended on the radar altimeter rather than vision for information about height above the terrain. He did this, he said, because windshield distortion made visual judgments of height above the ground unreliable at very low altitudes.

C. MULTIPLE IMAGES.

Several of the pilots had experienced multiple images at night, and found them to be a major distraction. One pilot, in particular, reported the appearance of duplicated landing light images to the left of the true position. In the F-111 the windshield curves downward to the left of the pilot's eye position. This accounts for the duplicated images being to the left.

D. COMPATIBILITY OF WINDSHIELD AND REFLECTOR GUNSIGHT.

One pilot reported difficulty in using the reflector-type gunsight, which combines the gunsight picture, reflected off a flat glass plate with the forward view seen through the curved windshield. The exact nature of the difficulty was not clear, but could be due to binocular deviation (see section 6) caused by the curved windshield. Other pilots said that they rarely used the reflector sight, and therefore had no comments to offer concerning problems associated with it.

E. COMPARISON OF WINDSHIELD OF F-111 AND OTHER AIRCRAFT.

The pilots who were interviewed had flown a variety of older aircraft. They were asked how they liked the windshields of other aircraft, by comparison with the F-111. The general answer was that they much preferred the windshields of the older aircraft. Specifically mentioned were better forward visibility, fewer and narrower blind areas caused by structural members, and better visibility over the side and to the rear.

9. ACCEPTANCE STANDARDS FOR OPTICAL PARAMETERS OF AIRCRAFT WINDSHIELDS

While the data on pilot visual performance and pilot ratings verify the need for vision to be as good as possible, they do not provide a suitable basis for the setting of optical standards for aircraft windshields. In actual practice, the standards which exist are rather arbitrary, and are based to a considerable extent on what the industrial production technology can provide.

Recommended standards for haze and light transmission were published by Glover (1955), based upon laboratory tests he conducted. The values he arrived at are shown in Table 4, taken from his report. Apparently the values in that table are for measurements made at zero angle of incidence. The recommended values for transmission increase with incidence angle in order to compensate for reduced transmission as the angle of incidence is increased. At the installed angles the recommended values in the highly desirable and acceptable categories would be about 66 and 60%, respectively. Unfortunately Glover does not give the data or analyses from which his values were derived.

TABLE 4. LIGHT TRANSMISSION AND HAZE VALUES (From Glover, 1955).

		WINDSHIELDS				CANOPIES	VISORS
		INCIDENCE ANGLE					
		55°	60°	65°	70°		
HIGHLY	Transmission	71%	74%	83%	99%	89%	90%
DESIRABLE	Haze	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
VALUES							
ACCEPTABLE IF	Transmission	66%	69%	78%	93%	83%	86%
OTHER FACTORS	Haze	1%	1%	1%	1%	1%	1%
TAKE PRECEDENCE							
MINIMUM VALUE	Transmission	64%	67%	75%	89%	77%	79%
MAXIMUM VALUE	Haze	2%	2%	2%	2%	2%	2%

Standards for the most important optical parameters have been provided for many years in US military specifications. A summary of optical requirements for windshields of US military aircraft, as provided in several specifications, is given in Table 5. Transparencies are classified into Type I, bullet resistant, general purpose; and Type II, bullet resistant for use with reflector-type gunsights. Within each Type there is a further breakdown into Grades A, general purpose, and B, high light transmission.

19

Note that the standards in Table 5, in most instances, are given for zero angle of incidence, rather than the installed angle. To determine what these values would be at the installed angle, the multiplication factors given in Figures 2 and 3 can be applied. It would be more realistic, however, to provide standards for the installed angle. It is understood that the testing of windshields for distortion, by aircraft manufacturers, is normally performed at the installed angle.

TABLE 5. OPTICAL ACCEPTANCE STANDARDS FOR TRANSPARENCIES OF U.S. MILITARY AIRCRAFT.

Optical Parameter	Standards	Source
Angle of Incidence	60° maximum throughout windshield	AFSC-DH-2-1 DN 3A1, 1969
	60° maximum in any part used for approach and landing	MIL-W 8175% (AS) 1970
	60° maximum at horizontal vision line	MIL-STD-850B 1970
Radius of Curvature Type II, A&B	Flat, minimum radius 500 ft	MIL-G-5485C, 1971
Deviation at 0° angle of incidence Type I Type II	3 min. maximum 31.5 sec. maximum	MIL-G-5485C
Deviation at installed angle, in gunsight area	±1.8 min. maximum	AFSC-DH-2-1 DN-3A1, 1969
Transmission at 0° angle of incidence Grade A	Range from 81% for ½" to 71.6% for 3" thickness	MIL-G-5485C
Grade B	Range from 85% for ½" to 78% for 3" thickness	MIL-G-5485C
Distortion	To be specified by procuring agency	MIL-G-5485C & MIL-G-25667B
	Deviation change per inch of surface at installed angle, for: Optically flat 1.0 min/in Flat 2.5 min/in Single Curved 4.0 min/in Compound 5.0 min/in	AFSC-DH-2-1 1969
Haze, at 0° angle of incidence	1% up to %" thickness 1.5% for %" to 1%" thickness	MIL-G-25667B, 1970

Corney in Great Britain has given considerable study to optical requirements for aircraft transparencies, and has offered tentative standards for use at the installed angles. Table 6 is taken from a recent report by Corney (1973). He offers standards for four categories of transparency, which are listed at the top of the table. At the bottom of the table are the proposed uses for the four categories. Considering that the values proposed by Corney are for the installed rather than zero angle of incidence, his values are in fair agreement with those given in Table 5, taken from US military specifications.

TABLE 6. ACCEPTABLE VALUES OF THE PARAMETERS ASSOCIATED WITH VISION THROUGH OPTICAL TRANSPARENCIES (Corney, 1973).

Parameter	Category I	Category II	Category III	Category IV
Optical Resolution value not to exceed	1 minute	1 minute	2 minutes	—
Haze value not to exceed	2.5%	2.5%	2.5%	—
Optical Transmission not less than	55%	55%	55%	50%
Optical Deviation	<5 minutes tolerance from and agreed value	<15 minutes	<20 minutes	—
Distortion		Change in slope not greater than 1 in 20	Change in slope not greater than 1 in 20	Change in slope not greater than 1 in 5
Binocular Deviation value not to exceed	10 minutes	10 minutes	10 minutes	—
Double Imaging	◄——Standards	to be decided	————►	
Scratches and Inclusions, etc.	◄——Provisional	Standards under	discussion	
Type of transparency (or area thereof)	Forward facing windscreen of the highest quality— suitable for weapon aiming	Forward facing and side panels for reconnaissance and search: forward panels for non-combat aircraft	Side panels for non-combat air-craft–canopies	Cabin windows

10. MEASUREMENT TECHNIQUES FOR TESTING WINDSHIELDS TO DETERMINE COMPLIANCE WITH OPTICAL STANDARDS

Most of the optical parameters discussed in this report can be measured by straightforward applications of geometry and physical optics. Such methods are described in most of the applicable military specifications. They can also be found in reports by Corney and Shaw (1971) and Corney (1973). Only one of the parameters listed in Tables 5 and 6, namely distortion, presents special problems concerning methods and units of measurement.

Most methods of measuring distortion involve a camera located at a position representing the pilot's eye position, the transparency, and a test grid at a suitable distance beyond the transparency. Beyond this basic setup, there is considerable variation in the methods that have been used. A fairly standard method uses double exposure, with and without the transparency in place. Any distortion will then be revealed by splits in the grid lines, and by bending of some of the lines. Several measurements are possible, such as the number of places where splits occur, the maximum width of the splits, and the maximum slope changes in grid lines.

Several variations of this basic technique have been proposed and used. For the Navy, Brown, Crumley, and Aisker (1954), Crumley, Atkinson and Fletcher (1954), and Lazo (1954) have used and recommended a technique involving a single photographic exposure with a two-hole mask over the camera lens. The windshield was placed at the appropriate place and installed angle with reference to the pilot's eye position. The acceptance criterion, or standard, was set in terms of the number of line splits that appeared in the photograph. In evaluating this technique, Smith (1958), concluded that the results were unreliable. The number of line splits varied too much with the test setup, the type of lens, the type of mask, the film processing method, and the judgement of the film reader in counting splits.

At the McDonnell Aircraft Company, St. Louis, Cocagne (1969) used a triple-exposure method. With the transparency located at the proper distance and installed angle relative to the camera, an exposure is made through the center of the windshield panel. Two more exposures are made with the panel moved upward, and then downward, two inches from the center position. Then another triple exposure is made through the center and two inches to the right and left of center of the panel. A maximum grid line growth of 0.014 inch, as measured on the triple exposure photograph, was taken as a rejection standard. Such growth was reported as indicating a maximum deviation change of 3.74 min.

Any of these grid photography methods involve considerable labor in measuring line splits, line growths, or line slope changes if the methods are to give accurate quantitative values. There seems to be no agreement as to which particular method of photography or analysis of the photograph is most satisfactory. Very often a mere visual examination of the photograph, or look at a grid through the transparency, will provide an experienced inspector with an adequate basis for accepting or rejecting a panel. Although such visual inspection is said to give good agreement with objective optical tests, it is too subjective to serve for acceptance testing.

11. EFFECTS OF WINDSHIELD GEOMETRY ON AIRCRAFT COST AND AERODYNAMIC EFFICIENCY

As mentioned in the introduction to this report the requirement for good pilot vision is in direct conflict with the need to streamline the aircraft to minimize aerodynamic drag. This conflict is particularly serious at supersonic speeds. As discussed earlier in Section 4 and shown in Table 1, recent USAF aircraft designed for high speeds have used curved windshields with angles of incidence exceeding 60°. In addition to having undesirable effects on pilot visual capabilities, as shown in this report, such windshields have probably added considerably to the aircraft cost. In this section some examination is made of tradeoffs among aerodynamic drag, windshield cost, and pilot vision. It must be pointed out, however, that aerodynamic and cost factors are outside both the basic purpose of this review and the technical competence of the author.

Among the reports found in this literature survey was a paper by Rubin (1968) that attempted to optimize windshield angle for high speed aircraft. Rubin pointed out that as the angle of incidence is increased the windshield cost for grinding and polishing must be increased in order to maintain constant values of deviation and distortion. Using this logic he generated an arbitrary curve of cost which increased very rapidly as incidence angle exceeded 60°. He also presented a curve of light

transmission like that in Fig. 3, and a curve of aerodynamic drag which showed very little drag reduction for incidence angles above 60°. Rubin further combined the three parameters, cost (C), light transmission (T), and drag (D) into a single figure of merit, namely T/D+C. Using his curves for C, T, and D, he showed that the combined fraction (T/D+C) reached a maximum at an angle of incidence of about 56°. Even when drag was given a weighting of 10 in the fraction (T/10D+C) the figure of merit reached a peak at an angle of incidence of about 60°.

While Rubin admitted that his curves of cost and drag were arbitrary, his general logic appears to be defensible. Certainly, to maintain equal values of deviation and distortion, windshield cost must go up as the angle of incidence is increased. Also, for comparable optical quality, curved transparencies are considerably more expensive than are flat panels. Cost data are beyond the scope of this report, and reliable cost comparisons for different aircraft windshields may be difficult to obtain. It is understood, however, that the windshield of the F-111 is a rather high cost item and that the replacement cost for a single panel has been in the range from $16,000 to $20,000. A large part of the high cost results from a very high rejection rate in the acceptance testing of the windshield panels, and from the manufacturing problems encountered in attempting to attain the optical quality required.

A major factor affecting cost is the size of the panels making up the windshield. As the area of the transparency increases, larger machines are required for forming and other manufacturing operations. Also, the problems of maintaining acceptable optical quality become magnified. Thus the costs increase in much more than a linear manner as the area becomes larger. An apparently small increase in angle of incidence, such as going from 60° to 65°, will cause a considerable increase in windshield area, and thereby a relatively high increase in overall cost.

While it is obviously important to minimize drag in a high speed aircraft, it seems worthwhile to examine what the drag cost would be for providing windshield geometry that would give improved vision for the pilot. Some data on the tradeoffs between drag and windshield geometry are available in a study from General Dynamics (1968) with reference to the windshield of the F-111B. After evaluating the aircraft for operation from aircraft carriers, the Navy specified a number of design improvements that would be required. Among the deficiencies identified by the Navy was that the pilot visibility from the F-111B was unacceptable for landing on carriers. The Navy, therefore, requested a "Cockpit module reconfiguration to provide about 3.7 degree improvement of (down) vision inclusive of a windshield angle change necessary to improve light transmission."

One of the major changes called for in the reconfiguration requested by the Navy was a change in windshield slope from 21.5° to 30° (i.e., from angle of incidence of 68.5° to 60°). The General Dynamics study report (1968), pages 93 & 94, presents their findings concerning the effects of such a change on aircraft drag. A summary of the resulting data, taken from that report, is shown in Fig. 10. At the top of the figure are side views of the windshield configurations which were studied. Presented in Fig. 10 are drag rise data at 0.75, 0.90, and 1.2 Mach for going from 21.5° to 30° windshield slope. For a curved windshield the drag increases caused by this slope change are shown to be $0 \Delta C_D$ at Mach 0.75, $0.0004 \Delta C_D$ at Mach 0.90, and around 0.001 to 0.0015 ΔC_D at Mach 1.2 For a windshield made up of flat panels (shaded curve in Fig 10) the drag rise is considerably higher. .

The overall drag, C_D, of the F-111 at supersonic speed is approximately 0.04. Based on this

value, the drag increase, caused by a change to a 30° windshield (60° angle of incidence) would be approximately 3% at supersonic speeds. At subsonic speeds the percentage drag increase would be considerably less. For a change from the present F-111 windshield to a flat configuration and a 30° slope it appears that the drag rise at Mach 1.2 would be about 8% of overall drag.
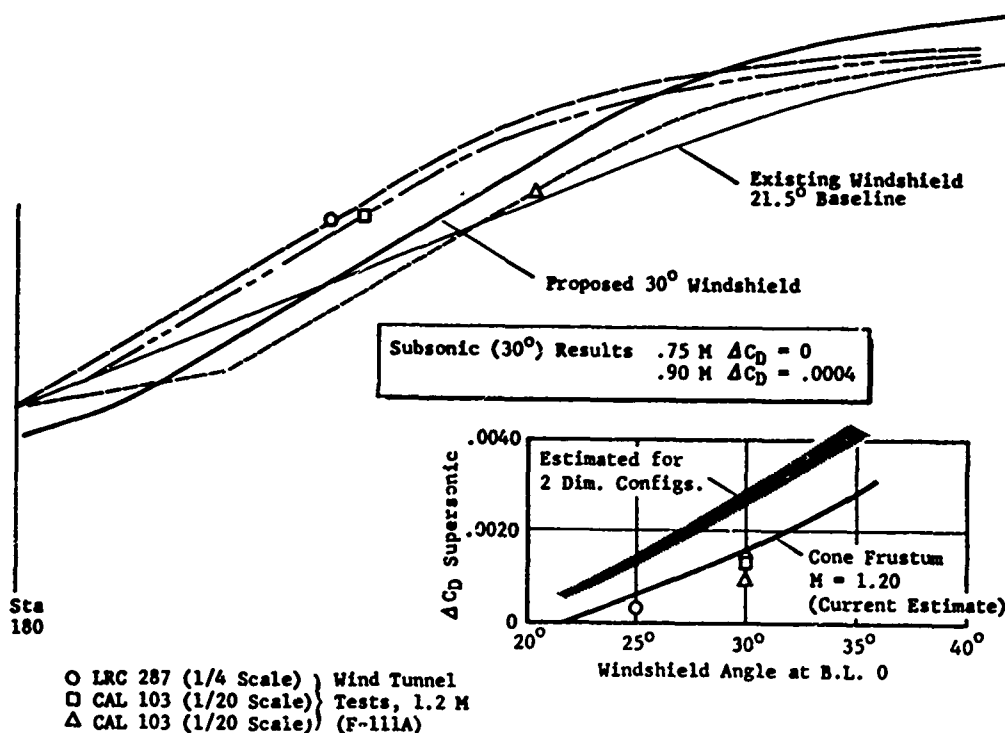
Figure 10. Effect of windshield geometry on aerodynamic drag for F-111B aircraft (from General Dynamics, 1967).

A reconfigured F-111B aircraft, providing the improved visibility, was never built. There was, therefore, no chance to follow up and verify either the predicted increase in drag or the improvements in visibility for the pilot. It would seem, however, that an overall drag rise that is near zero at subsonic speeds, and only 3% at supersonic speeds, would not have been too high a price to pay for acceptable visibility for the pilot. Although quite beyond the scope of this report, it would seem worthwhile to conduct a cost/effectiveness study to evaluate the effects of windshield geometry on aerodynamic drag, aircraft cost, combat effectiveness, and flight safety.

12. DISCUSSION

This literature review shows how the slope and curvature of aircraft windshields produce optical effects that have an important influence on the quality of pilot vision in the forward direction. Un-

fortunately there is a basic incompatibility between the windshield geometry that is required for good pilot visibility and that which causes minimum drag at high speed. The optical effects that degrade pilot vision are governed by physical laws, which are just as fundamental and invariant as are the laws of aerodynamics with which they come in conflict. Aircraft designers and their customers, as a consequence, are faced with a difficult choice among alternative windshield designs. Designs that maximize aerodynamic efficiency cannot avoid penalties to pilot vision through the types of optical degradation discussed in this report. It is hoped, however, that this review will be of assistance to aircraft designers and their customers in finding acceptable compromises in the choice between pilot vision and aerodynamic efficiency.

For a single-place or tandem aircraft there are two common types of windshield design: (1) A flat panel sloping up to a canopy bow just ahead of the pilot, with curved panels at each side; and (2) A one-piece curved wrap-around panel. There are advantages and disadvantages to each design.

The first and older design, used on such aircraft as the F-4 and F-14, both designed to basic Navy requirements, provides flat glass in the most critical area. This is the area for seeing directly ahead, for visual sighting using a reflector-type gunsight, and for viewing of a heads-up display of flight data. The use of flat glass avoids the optical problems inherent to curvature as discussed earlier in this report. On the other hand, with this type of windshield there is obstruction of vision from the framing that joins the flat front panels to the curved side panels.

The second and newer type of windshield design, used on such aircraft as the T-38, F-5, and F-15, is more efficient aerodynamically. It also avoids the visual obstructions of the framing around a flat front panel, and thus provides a clear visual field back to the canopy bow. The use of curvature, however, results in increased deviation and distortion effects, and introduces binocular deviation with consequent complications in the use of a reflector-type gunsight or heads-up display. Optical degradation of pilot vision with this type of windshield will be minimized by using an angle of incidence of 60° or less, using single curvature, and placing the pilot's normal eye position at the center of the curvature in the horizontal plane. It is understood that this type of one-piece wrap-around windshield is considerably more expensive than the older three-piece design. The cost is higher for initial development and throughout the life of the aircraft.

For side by side cockpits the windshields are normally made up of a front panel before each pilot, plus additional panels at the sides. The front panels are either curved or flat, are joined at the midline, and normally slope both upward and to the side. Such an arrangement, with either flat or curved panels, provides good forward vision if the angles of incidence are relatively low in both the vertical and horizontal planes. At extreme angles of incidence combined with curvature, such as in the F-111 and B-1, pilot vision is considerably degraded by deviation, distortion, low transmission, and multiple images. The deviation and multiple image problems are magnified by having the pilot's eye position considerably displaced from the center of the curvature in the horizontal plane. The optical degradation would be somewhat reduced by use of a "double bubble" arrangement in which the eye position for each pilot is at the center of the arc, in the horizontal plane, for his windshield panel. But such an arrangement would probably be less efficient aerodynamically, and might create cross-cockpit visual problems. Whether the windshields are curved or flat, the quality of pilot vision is rapidly degraded as angles of incidence are increased above about 60°.

25

Presumably because of the need for making visually guided landings on aircraft carriers, the Navy has maintained stricter optical criteria for aircraft windshields than has the Air Force. The Navy has continued to require flat panels for forward vision and angles of incidence of 60° or less. This difference in design requirements is reflected in the data shown in Table 1. It appears also that the Air Force has been somewhat more lenient than the Navy in permitting deviations from existing windshield design standards as published in the current design specifications (See Table 5).

13. SOME SUGGESTIONS FOR FURTHER STUDY

As a result of conducting this review the author has a number of suggestions about further efforts that would benefit aircraft designers and their customers in making design decisions for future aircraft. First, it would be very helpful to have a mathematical model to aid in making the tradeoffs among aerodynamic efficiency, cost, and pilot visual performance as they relate to windshield configuration. For such a model to have much real value, more and better data are needed concerning the effects of varying degrees of visual degradation upon flight safety and combat efficiency. Analysis of existing accident data at the Air Force Inspection and Safety Center, Norton Air Force Base, would probably provide useful data on how visual degradation affects cost through accident losses. An appropriate operation analysis, based upon combat data in Vietnam, could probably provide data on how visual degradation affects combat efficiency and survival rates. A mathematical model on windshield design should also include data on windshield manufacturing and replacement costs. For this purpose cost data for current aircraft windshields would give useful estimates.

Another type of study that should help in making future windshield design decisions would be a survey of pilot opinions. Many pilots have flown a variety of aircraft with different windshield configurations. Their observations and preferences concerning windshield design would provide a valuable set of data. For example, there are many pilots who have flown both T-38s, with one-piece wrap-around windshields, and F-4s (or other aircraft) with a flat front and curved side panels. All pilots of F-111s will have had experience with windshields in other aircraft and could make helpful comparisons. Probably most pilots would have helpful observations about vision through curved and flat windshield panels. Certainly, the pilots opinions and preferences deserve consideration in choosing windshield designs.

For the optical acceptance testing of windshields there is still no agreement on the best method of measuring and quantifying distortion. If further comparisons were made among the existing methods then it would probably be possible to select one as the most discriminating, reliable, and efficient to use. Or possibly a new approach, such as laser beam scanning, would offer a better way to measure distortion.

14. SUMMARY

This report provides a review of the literature on pilot vision as affected by the geometry and optical characteristics of aircraft windshield design. Included in the report is some examination of military standards and optical testing of windshields. The major findings of the literature review are as follows:

(a) Windshield geometry, in terms of slope and curvature, that is optimum for high speed flight results in serious degradation in pilot vision in the forward direction.

(b) The optical effects of windshield geometry follow well-known laws of physical optics. Those effects which cause significant degradation of pilot visual capabilities are deviation, distortion, binocular deviation, reflections, multiple images, haze, transmission loss, and reduced resolution.

(c) For minimal degradation of pilot vision, the angle of incidence should not exceed 60° (i.e., slope not less than 30°), and the transparent panel should be flat rather than curved. Vision deteriorates rapidly as the angle of incidence exceeds 60°, and with curvature of the transparency. If curvature is used, the radius of curvature should be as large as possible, curvature should be simple rather than compound, and the pilot's eye position should be near the center of the curvature.

(d) The use of a curved windshield results in binocular deviation (i.e., unequal deviation for the two eyes). Because of this, the use of a reflector-type gunsight or heads-up display results in double images and sighting errors, unless suitable compensation is provided in the optical system of the heads-up display.

(e) The use of a curved windshield, high angle of incidence, and a pilot eye position displaced from the center of curvature produces problems of optical distortion and multiple images, which severely degrade pilot visual performance.

(f) Windshield geometry and optical quality called for in existing military standards and specifications are adequate, and if complied with, provide good pilot vision in the forward direction. Generally, however, these specifications define optical quality for 0° angle of incidence, rather than the installed angle. A revision of military specifications to provide optical standards and test methods applicable to the installed angle would be desirable.

(g) There is, currently, no agreement as to the best method for measuring distortion in the optical testing of windshields, although a variety of methods are available. Further study, and possible agreement on a standard method for measuring distortion, appears to be needed.

(h) There is, currently, no adequate method of selecting an optimum windshield design, based on considerations of aerodynamic efficiency, pilot visual performance, and cost. It is suggested that efforts be directed toward development of a mathematical model for making tradeoffs among these three parameters.

(i) As an aid in the selection of windshield configurations for future aircraft, it would be helpful to have a systematic collection of pilot opinions, based upon their experience in flying different aircraft.

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